NATIONAL UNIVERSITY OF
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PhD THESIS – ABSTRACT

Theoretical and Experimental Research on the Dynamic Behavior of Laser-Based Medical Systems

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Thesis summary

Due to the technological advancements in electronics over the past decade, which have enabled the use of billions of transistors on a single integrated circuit [1,2], there has been an exponential development of computing microsystems, processors, and microcontrollers. With a high-performance computing system, offering miniaturization and custom design capabilities, fields based on integrated circuits (IC) have also seen consistent progress in recent years. For example, the laser industry is currently developing laser beam generation systems with powers in the petawatt range [3], used in nuclear physics, based on the method of "generating ultra-short high-intensity optical pulses" proposed by Gérard Mourou and Donna Strickland in 2018 [4].

Another major benefit brought by the evolution of electronics and its accessibility to the general public is represented by medical monitoring devices, such as smart bracelets and watches, which contain miniature sensors and specialized algorithms for measuring stress levels, blood oxygen saturation, heart rate, and, last but not least, sleep quality. Innovation also continues in the field of specialized medical systems, such as teleoperated robots for complex surgical procedures [5–7], as well as in manually operated medical devices, which now benefit from assistance systems and active vibration damping mechanisms [8–10].

This work proposes a combination of two fields—lasers and medicine—by analyzing and designing a manually operated laser device with primary applications in microsurgery. The system aims to fully exploit the essential features of lasers in medical applications: contactless surgery, a focal spot in the tens of microns range, high pulse power, and high repetition rates. The laser device will be equipped with a vibration compensation system to ensure a precise, ultra-stable surgical procedure.

Current microsurgical systems rely on the surgeon's ability to perform extremely fine movements with minimal vibration at the end effector. This requirement imposes the need for highly skilled personnel and limits work duration, the types of microsurgical procedures, and the quality of those performed. Therefore, efficiently reducing involuntary or unwanted movement in microsurgery (the surgeon's hand tremor) would not only improve the accuracy of current procedures but could also open the path to new types of surgeries. Moreover, creating a mobile operating device would increase the surgeon's flexibility and enhance the possibility of performing procedures in economically disadvantaged or resource-limited areas.

Vitreoretinal microsurgery has been the primary driver of laser beam applications in surgery because it is among the most demanding specialties in terms of precision manipulation and, until now, has required robotic positioning systems. Transitioning from mechatronic-assisted to manual operation imposes limitations on working precision due to the human body's anatomical construction. These limitations are largely due to what is called physiological tremor—an involuntary, oscillatory, and rhythmic movement resulting from alternating contractions of agonist and antagonist muscles, triggered by signals from the nervous system [11,12]. By using a sensory system to measure such signals, various active damping mechanisms can be employed to suppress the tremor and improve surgical accuracy. For optimal mechanical structure and actuation method determination, it is necessary to analyze existing positioning solutions that allow for miniaturization.

As a result, the objectives of this doctoral thesis are as follows:

- Analysis of the problem (physiological tremor)
- Analysis of tremor compensation methods
- Analysis of mechanical systems used for vibration damping
- Analysis of actuation methods and mathematical modeling
- Design of a macro-scale prototype
- Evaluation of miniaturization possibilities

This work presents a theoretical and experimental analysis of the development of a demonstrative device for active hand tremor suppression. The optomechatronic device is intended for medical applications, where even small tremor amplitudes have a significant impact. To develop such a device, Chapter 1 includes a thorough analysis of the existing literature on vibration compensation systems and currently available commercial devices. Based on studies mentioned in references [6–16], the dynamic parameters that describe the hand's oscillatory movement—i.e., tremor—have been identified, along with the input parameters required for the vibration compensation system. Given the medical field in which the proposed device is intended to be used, the research focuses on compensating micrometric amplitude vibrations (approximately 150 μm peak-to-peak) within a frequency band of 5 to 15 Hz.

From the analysis of the existing literature, two main research directions have emerged:

1. Selecting suitable sensors and implementing digital signal processing to determine the direction, phase, and amplitude of oscillations.

2. Developing a micro-positioning system capable of performing minimal displacements of 300 µm (±150 µm) and providing excellent dynamic response within the tremor-specific frequency band.

Chapter 2 begins by introducing a novel experimental method to measure hand tremor, confirming the specialized literature reviewed in Chapter 1. Although the test subjects were not trained surgeons, the results confirmed the frequency band and determined a translational vibration amplitude of 150 µm and a maximum hand rotation angle of 0.3°. After the experimental tremor analysis, the chapter discusses potential compensation scenarios for different device types that could be developed.

The compensation scenarios presented in Chapter 2 consider various configurations and geometries for the optomechatronic device. 3D printing of these prototypes played a key role in continuing the research and contributed to a better understanding of the phenomenon.

In Chapter 3, the structure and geometry of the compensation device are defined, and the development of a demonstrative system is proposed to illustrate the physical phenomenon as clearly as possible. A macro-scale system was chosen, incorporating a compliant amplification mechanism specifically designed and developed for the intended application.

Theoretical analysis, both through analytical mathematical modeling and more advanced methods such as finite element analysis (FEA), confirms the feasibility of the proposed compensation principle and supports the transition to experimental system analysis. Furthermore, the comparison of theoretical analysis methods confirms their validity, with modeling errors below 3%.

Chapter 4 addresses the experimental analysis of the mechanical subassemblies of the device from structural, static, and dynamic perspectives. It begins with the practical realization and analysis of the mechanical amplifiers. The experimental results, obtained through innovative testing techniques (displacement mapping via Digital Image Correlation using the ZEISS ARAMIS system combined with a loading machine) as well as traditional modal analysis setups, confirm the correlation with the theoretical analysis from the previous chapter.

Static and dynamic transmissibility analysis of vibrations showed errors of 8% and 3.2%, respectively, confirming that the control structure was properly designed and can be used for the final assembly and demonstration of the compensation principle. Frequency response analysis demonstrated that the resonance frequencies of the mechanism and its subassemblies do not interfere with the critical operational frequency band of the final application. It was confirmed that the mechanism and piezoelectric actuators can be successfully integrated into the laser positioning device, ensuring the precision and stability required for developing the prototype of the laser scalpel with active hand tremor suppression.

Chapter 5 presents the final assembly and theoretical analysis of the joints connecting the device's moving parts. The central joint was designed to minimize the laser scalpel's diameter, allow the laser diode to rotate at a minimum angle of 0.2°, and include an inner tube for routing power and control wires.

The spherical joints (metal wires) required additional experimental testing due to computational limitations. This involved experimentally determining the final positions of the contact points between the piezoelectric actuator and the two arms of the mechanical amplifier (lower and middle arms). Using these points as input for the finite element analysis enabled sizing the height of the metal wire that serves as a spherical joint and allowed completion of the final assembly.

Chapter 6 presents the verification of the vibration compensation hypothesis using a dedicated experimental stand. The most complex part is the post-processing of images that capture laser spot displacement and the analysis of this displacement through various stages.

System calibration plays a crucial role in validating the measurements and is the first step in verifying the compensation hypothesis. The displacement-voltage characteristic indicates the maximum tilt angle obtained, and the manual compensation strategy analysis confirms an approximately 70% reduction in the vibration effect on the laser spot.

After confirming the vibration reduction hypothesis, Chapter 7 discusses the compensation strategy for the developed structure and analytically determines the relationships between translational and rotational vibration amplitudes and the rotation angles of the mobile platform.

Based on these compensation relationships and the system geometry, a future miniaturized version of the device can be developed, streamlining the development process. The system of equations must be integrated into the final compensation algorithm, along with experimentally derived relationships discussed in Chapter 8.

Chapter 8 contains the experimental analysis of vibration transmissibility for a single amplifier and the compensation method for the target frequency band. This test determines the compensation signal's actual frequency, amplitude, and phase shift relative to the input signal. The test stand is automated using a custom LabVIEW program, and post-processing of acquired data was performed in MATLAB.

All these tests confirm, both at subsystem and system levels, that the concept proposed at the beginning of the research is feasible and can be implemented in future specialized microsurgery devices. This approach would significantly improve surgical performance and may also open the path for new procedures currently performed exclusively by robots.

Future research should focus on system miniaturization and the development of a complete computational algorithm. Eliminating the amplification mechanism and introducing more compact actuators with equivalent travel is essential to match the form factor of current laser scalpels. Based on the theoretical (mathematical model) and experimental research presented in this work, the development of such an optomechatronic device for medical use can be significantly accelerated.

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